# Comparison of Methods for Evaluating Airport Pavement Roughness

The correct and timely assessment of the airport pavements surface quality is fundamental to verify the presence of any irregularities that could be detrimental to aircraft operations. Furthermore, a rough runway can increase the maintenance costs of both pavements and aircrafts landing gears, due to the increment of dynamic loads and fatigue phenomena on airplanes structural elements, reducing their service life. Nowadays, the maintenance budget available by airport agencies is very restricted, thus, it is necessary to define properly the type and the extension of interventions able to restore runway evenness.

In this paper, the roughness assessment of real runway profiles is carried out using first of all BBI and IRI but also ProFAA simulation model, with particular attention to Cockpit Vertical Accelerations, underling the different impact on airport pavement management of the results provided by them. In particular, very low correlations for the whole sample of examined profiles were found between IRI and BBI ($R^2$=0.11) and between IRI and cockpit vertical acceleration ($R^2$=0.03), while a better correlation was obtained between BBI and cockpit vertical acceleration ($R^2$=0.59). Neglecting runway profiles characterized by long wavelengths roughness, a very high correlation between IRI and BBI ($R^2$=0.91) was found, that underlines their different sensitivity to long wavelengths. In particular, it was found that for roughness characterized by low wavelengths, the IRI method seems to be more conservative than BBI. In addition, two different IRI acceptance thresholds were taken into account, one used in South Africa (2 m/km) and one adopted in Canada (2.7 m/km). For the whole profiles sample, little differences were found in their runway sections evaluation (about 4%) compared to BBI method; while, considering the reduced sample where profiles characterized by long wavelengths roughness were excluded, the use of IRI limit of 2 m/km would seem to be too conservative.

Keywords: Runway Roughness; Pavement Maintenance; Profilometers; Pavement Roughness Evaluation Criteria; Boeing Bump Index (BBI); International Roughness Index (IRI); Profile Evaluation

## Introduction

The correct and timely assessment of the airfield pavements surface quality is fundamental to verify the presence of any irregularities that could be detrimental to aircraft operations; some problems in air transport management can be caused by runway and taxiway pavement unevenness in consequence to:

- increment of the stresses on aircraft structural components, thus, bringing them to local damages and possible fatigue failure phenomena (ENAC LG 2015/003-APT);
- increment of the loads on pavements, reducing their service life (ENAC LG 2015/003-APT);
- induction of excessive pitch and roll motions in aircrafts, that can interfere with their operational performance and control decreasing the safety (ENAC LG 2015/003-APT);
- reduction of passengers comfort. This problem, although important, is often not a significant issue since the degree of discomfort is small and the time of exposure is limited to a few seconds (FAA Advisory Circular No. 150/5380-9);
- vibration problems that can make the reading of the instruments difficult for pilots (ENAC LG 2015/003-APT).

An appropriate pavement management system should consider the indirect costs of these consequences, with particular attention to the dynamic loads increment and above all, to aircraft fatigue due to rough pavements. In fact, the effects of accelerations due to runways roughness are exponential in terms of cumulative damage induced on aircraft landing gears (McNerney and Harrison 1995).

The attention to this problem is very important in military aviation where both airports and aircrafts maintenance costs are managed by the Air Force, which thus needs to find the optimum between interventions on pavements and/or on aircrafts.

In civil aviation, instead, the attention is mainly focused on the damage induced by aircrafts on runways and taxiways, evaluating aircraft operation fees for airport services as a function of the detrimental effects on pavements (Feighan and Reynolds-Feighan 2004, Morgado and Macário 2012). Of course, this is a correct approach considering the costs that airport agencies have to cover for rehabilitation or renewal interventions on pavements, but it should be also take in account the major costs that air companies have to pay due to a not adequate level of pavement roughness.

Nowadays, several profile analysis methods are available to measure and assess airport pavements roughness. The International Roughness Index (IRI) (defined in the ASTM E1926-2008), which is designed and developed for road roughness evaluation is one of them. IRI is widely used in road roughness assessment and, often, it is used to evaluate airfield pavements surfaces, even if it is not recommended. In fact, some countries like Italy (ENAC 2015) and Brazil (ANAC 2012) involve the use of IRI to evaluate longitudinal roughness of airfield pavements; furthermore, other evidence on the use of this index in other countries, like Mexico (González Saucedo and Rodriguez Parra 2007) and South Africa (Horak et al. 2010, Emery et al. 2015) can be found in literature. In addition, some countries like Canada (Transport Canada AC 302-023), adopt the Ride Comfort Index (RCI) whose correlation with IRI was established; thus, starting from IRI values it is possible to determine the corresponding RCI values. Even if IRI is not recommended in the International Civil Aviation Organization (ICAO) regulations, the application of IRI as an indirect method to evaluate roughness on airfield pavements is a strong temptation (Emery et al. 2015), because there is a large experience on IRI equipments for road measurement. In particular, there are many vehicle-mounting inertial laser based on non-contact devices that can easily and quickly measure the roughness of airport pavement, so to calculate the corresponding IRI values.

A more adequate method for airfield pavements roughness assessment was proposed by the Boeing Company (DeBord 1995), also known as “The Boeing Bump Criteria”, which is based on considerations on aircraft fatigue induced by rough pavements. The method was adopted in FAA guidelines and procedures for measuring airfield pavement roughness (Advisory Circular No. 150/5380-9), providing an index named Boeing Bump Index (BBI). To calculate the BBI, it is necessary to measure some pavement profiles by means of contact devices that are able to measure the true profile of pavements. Choosing the appropriate device is very important in order to obtain correct and significant results as described by Song et al. (2014).

## Study Objectives

In this paper, a comparison between BBI and IRI approaches was carried out with the goal of underlying the different roughness evaluation provided by them. In addition, the effect of some acceptance thresholds on the assessment of airport pavement roughness was analyzed. In fact, the judgement of a runway profile, as acceptable or not, leads to different maintenance actions that may affect Airport Pavement Management System (APMS). Finally, considering the importance of pilots’ reports on runway unevenness evaluation, simulation models representative of aircraft response were also considered in order to assess the capability of IRI and BBI to describe cockpit vertical accelerations induced by irregularities present along the runway profile.

## Roughness Definition and Measuring Equipment

Longitudinal and transverse profile measurements are required to assess pavement roughness. A definition of roughness is provided by the ASTM E867-2002

“Terminology Relating to Vehicle-Pavement Systems”: “*The deviations of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads, and drainage, for example, longitudinal profile, transverse profile, and cross slope.*” Sometimes some authors prefer to use the opposite term: smoothness, that is the absence of undulations on the pavement surface.

The term roughness, however, should not be confused with the micro-, macro- and mega-texture characteristics of pavements surface, whose thresholds limits in the wavelength domain are described in literature (PIARC 1987, Loprencipe and Cantisani 2013) and shown in Figure 1. Each one of these wavelength ranges covers important issues related to the aircraft-pavements interaction. In fact, macro and micro texture are important to activate friction while plastic deformations are related to manoeuvrability. The failure of both of them can lead to aquaplaning problems, but the excessive presence of the second category can induced user discomfort. In addition to these ones, there is roughness, the main topic of this paper, which is very important because it can induce several detrimental effects like fatigue on landing gears, increasing in tire consumption and dynamic loads increment on pavement (Bonin et al. 2007, Cardoso 2002). As can be seen in Figure 1, the range of wavelength affecting aircrafts response is wider than the one for road vehicles and it includes long wavelengths due to the high speed of traveling and the distance between the front and rear landing gears.

Airfield pavement roughness is grouped by FAA (Advisory Circular No. 150/5380-9) in two main categories based on the dimensions and the frequency of surface deviations: single event bump and profile roughness. The first one includes isolated events characterized by changes in pavement elevation occurring in a relatively short distance (100 m or less) and they are felt by airplane components and occupants as a shock or sudden jolt; while in the second category, random surface deviations over a portion of the runway are included. Profile roughness can reduce braking action, increase fatigue on airplane components, affect cockpit operations and cause discomfort to passengers.

There are three different approaches that can be used for the assessment of pavements surface quality: objective profile measurements devices, response type systems and subjective panel ratings (Kanazawa et al. 2010). Not considering in this paper the last type, a general classification of roughness measurement devices was developed by Sayers et al. (1986), defining the following four classes:

- Class I: Profiler devices belonging to this class provide measurements that can be referred to an external level. They are also known as “true profile” systems. Some examples of class I equipment are Dipstick, Automated Rod and Level (AR&L) and Walking Profiler G2;
- Class II: These systems are used to measure “relative” profiles, because they are not related to absolute external reference. These kind of devices can be either contact or non-contact profilometers. They have to be calibrated with profiles measured by Class I survey. The Automatic Road Analyzer (ARAN) and the non-contact lightweight profilers LISA and T6400 belong to this class;
- Class III: These systems are in general called Response-Type Road Roughness Measuring Systems (RTRRMS). The measures from these kind of devices should be linked with indexes like IRI, through adequate experimental correlation equations. The calibration of these systems can be made using both Class I and Class II survey. Examples of these devices are the Analyseur de Profile en Long (APL) and the Bump Meter;
- Class IV: In this class we find subjective ratings and un-calibrated measures that can be obtained riding on pavement sections or through a visual inspection.

The required performances for Class I and Class II devices are defined in ASTM E950-1998.

In the assessment of airfield pavements roughness, it is important to measure all the undulation wavelengths characterizing the pavement surface in order to evaluate their influence on aircraft response. The only way to satisfy this requirement is to measure true profiles, obtainable using Class I devices. In fact, most of the Class II systems are designed to assess road pavements roughness and thus, they are not able to capture long wavelengths that are specifically detrimental for aircraft operations. Actually, most of Class II devices can measure maximum wavelength next to 50 m, while for runway pavements, wavelengths up to 100 m are significant. One possible solution to avoid this problem is to combine Class II measurements with rod and level absolute elevation measures (using, for example, a 5 m sample step), in this way it would be possible to capture the whole wavelength range of interest.

## Evaluation Criteria and Performed Analysis

Nowadays, several profile analysis methods are available to measure and assess airport pavements roughness. One method, used as new pavements smoothness acceptance criteria for the evaluation of the construction quality, is the Straight-Edge Criteria (SE), which is based on the measure of the distance between the road surface and a straightedge laid on it. Various straightedge lengths in the 3 to 7.8 m range are currently used in the airfield practice, as described by Song and Hayhoe (2006) and Múčka (2012). In particular, the length equal to 3 m is used in the ICAO guidance in Annex 14, while in the Federal Aviation Administration (FAA) Advisory Circular AC 150/5370-10G (containing smoothness specifications for new pavements), straightedge lengths of 3.66 m (12 feet) and 4.88 m (16 feet) are respectively used for new asphalt and new PCC pavements. Beside to these straightedges, the use of the California Profilograph is very popular but it can only assess irregularities detected using a 7.62 m (25 feet) rolling straightedge reference, and because of its limitations (Gerardi et al. 2007) it cannot be used for the ICAO and FAA new construction criterions.

Another profile evaluation method, still used by many airport agencies in several countries (e.g. Brazil, Canada, South Africa and Italy), is the IRI, developed from a World Bank study (Sayers 1995). IRI is based on a mathematical model called quarter-car and developed to assess the ride quality on road pavements. The evaluation is performed by model, calculating the simulated suspension motion on profile and dividing the sum by the distance travelled according to the equation (1):

$$IRI = \frac{1}{l}\int_0^{l/v} \left|\dot{z}_s - \dot{z}_u\right| dt \tag{1}$$

where $l$ is the length of the profile in km, $v$ is the simulated speed equal to 80 km/h, $\dot{z}_s$ is the time derivative of vertical displacement of the sprung mass in meters and $\dot{z}_u$ is the time derivative of vertical displacement of the unsprung mass in meters. In this way, an index having slope units (e.g. m/km, mm/m) is given. The model is capable to detect and evaluate a limited range of wavelengths. In fact, the response goes down to 0.5 for wavelengths equal to 1.3 m (0.77 cycles/m) and 30.5 m (0.033 cycles/m), although there is still some response for wavelengths outside this range (Sayers and Karamihas 1998) as shown in Figure 2. Because of the characteristics of the mathematical model used for its calculation, IRI could be not suitable of evaluating airport pavements for neither long wavelength roughness nor aircraft response; in fact, aircrafts mainly respond to roughness events in pitch, therefore, a single suspension model like the quarter-car cannot properly describe aircraft ride quality. According to some authors (CROW Report D06-01), however, IRI can be used to evaluate taxiways, instead than runways, because the aircraft speed on the first one is relatively low (20-30 knots, equivalent to about 37-55 km/h) if compared to runway speed (greater than 100 knots, equivalent to 185 km/h). For this reason, the maximum wavelength affecting aircrafts response is significantly lower in the taxiway pavement. For example, Cardoso (2007b) has investigated the interaction between the B737-400 and the runway pavement surface, with particular attention to resonance problems. He estimated that the B737-400 response frequency was approximately 0.7 Hz, thus, the critical wavelengths at different aircraft velocities were calculated. In particular, it was found that at 100 knots the critical wavelength was equal to 73 m, while at 20 knots it was lower and equal to 15 m; that is a wavelength within the range of IRI operability. About this aspect, Woods and Papagiannakis (2009) performed a comparison between several conventional roughness indices (e.g. Ride Number, IRI and BBI) with aircraft response parameters (center of gravity acceleration, pilot station acceleration, nose and main gears pavement loading), calculated considering two simulation speeds of 20 and 45 knots (respectively equal to 47 and 82 km/h). In this case, they found that the use of IRI seems to be able to capture peak aircraft response. However, it should be underlined that also taxiways can induce detrimental effects on aircraft response due to long wavelength, which cannot be captured by IRI. In any case, highways IRI thresholds cannot be applied to taxiway without modification (Haynoe 2016).

Another method for the airfield pavements roughness assessment was proposed by the Boeing Company (DeBord 1995), also known as "*The Boeing Bump Criteria*", and then, even if slightly modified, officially recognized by the FAA and ICAO, respectively, in the Advisory Circular No. 150/5380-9 and in the Amendment 10 to ICAO Annex 14 – Attachment A, Guidance material supplementary to Annex 14, Volume I, which one was incorporated in 6th edition of the Annex 14 (ICAO 2013). In order to assess the aircraft response to single bump event it is chosen to use the BBI method defined by the FAA. Developed starting from the Boeing Company criterion, it is based on considerations on fatigue airplane components induced by rough pavements. The processing steps performed for the calculation of the BBI are the same as the ones described in the FAA Advisory Circular No. 150/5380-9 and depicted in Figure 3a. Then, the belonging zone (Acceptable, Excessive and Unacceptable) for each section is found, according to the bump length specific threshold limits shown in Figure 3b. The Boeing roughness criterion describes unevenness based on a single event condition and it was developed considering a heavily loaded aircraft approaching take-off speed, which is the most critical condition for runway roughness. It is based on data relating to large commercial jet aircraft. This approach is capable of assessing the influence of all the most critical wavelengths on the aircraft response, including all the wavelengths analyzable through the various straightedge methods previously described; but it cannot evaluate the effects of the presence of a series of irregularities on the pavement surface. Furthermore, the aircraft response is strongly influenced by the speed of transit and by the airplane structural design and physical characteristics, while the Boeing approach provides a unique criterion that is meant to describe the general condition of a runway rather than to analyze the response of each single aircraft type.

In order to overcome these limits, many authors recommend calculating the interaction between pavement and different aircraft types using a specialized software able to simulate the aircraft response on a measured profile, following the ±0.4g criterion (CROW Report D07-03a). Although this approach provides useful description of the aircraft response to pavement roughness that can be used to compile an adequate maintenance plan, it is not incorporated in FAA and ICAO standards, so airport agencies are not forced to adopt it.

Among all this approaches, although its use is not recommended to assess airport pavement roughness, the use of IRI is still very frequent.

The present work focuses on the analysis of several profiles sections, calculating for each of them both the IRI and the BBI. To compare the description of the pavement surface quality provided by IRI, that determine a single value characterizing the whole section length, in this study it was decided to calculate the BBI for all the points belonging to the profile section, then picking up the maximum value among them.

## Results and Discussions

### *Analysis of artificial runway profiles*

A preliminary evaluation of the single wavelength influence on IRI and BBI was carried out considering several hypothetical sinusoidal profiles. For this purpose, a wavelength range from 1 m to 200 m (with a step of 1 m) and an amplitude range between 1 mm and 200 mm (with a step of 1 mm) was investigated; thus, a total number of 40000 sinusoidal profiles were examined. To compare the two above-mentioned indexes, the IRI upper acceptance threshold was fixed equal to 2.0 m/km, considering for this hypothetical preliminary study the IRI limit indication provided by Sayers and Karamihas (1998). For BBI, the thresholds defined in AC 150/5380-9 were used.

It should be specified that the upper limit of "*excessive zone*" depicted in Figure 4b, is fixed constant and equal to 1.25; while, as reported in Figure 3b, for low wavelengths the threshold value is variable. This choice is made to simplify the reading of the plot and it does not provide any influence on the global results. Furthermore, most of the sinusoids present the maximum BBI value in correspondence of bump length greater than 10 m.

In Figure 4 the results of this preliminary study are depicted. Figure 4a highlights the inability of IRI to take into account the effects of long wavelength irregularities on aircrafts response. In fact, for wavelength higher than 50 m, IRI considers as acceptable the analyzed sinusoidal profiles in all the amplitudes range. In addition, as can be seen in Figure 4a, even if IRI thresholds lower than 2 m/km are picked up, the highest wavelength affecting IRI calculation is equal to about 60 m. On the contrary, in Figure 4b, the capability of BBI to take into account the effects of the long wavelengths is shown and, in particular, the whole range of interest for aircraft response is adequately assessed. Thus, the use of IRI for the airfield pavement unevenness evaluation can lead to incorrect assessments because of underestimating or not considering the contribution provided by some wavelengths. Consequently, two pavement profiles having similar IRI values may induce completely different effects on aircrafts response. This issue is a limitation of IRI also known in road applications and it was described for motor vehicles by Kropáč and Múčka (2005), by Cantisani and Loprencipe (2010), by Múčka and Granlund (2012) and by Loprencipe and Zoccali (2017). Merging Figure 4a and 4b plots between them, it is possible to locate different zones in which the evaluations of the sinusoidal profiles unevenness, obtained using IRI and BBI, are in agreement or not (Figure 5).

### *Analysis of real runway profiles*

Three longitudinal profiles belonging to three different real runways, measured on the centre alignment and having two of them length equal to 3.0 km and the other one length of 2.7 km, were obtained using Class I devices with a survey interval of 0.25 m. The aforementioned profiles, characterized by different roughness level, were divided in sections of fixed length equal to 100 m as required in South Africa (Emery et al. 2015) and Canada (Transport Canada AC 302-023). The IRI acceptance thresholds for single runway section of 100 m are respectively equal to 2 m/km (Emery et al. 2015, Horak et al. 2010) and equal to 2.7 m/km, that is equivalent to a RCI rating of 5.0

(Mesher et al. 2015). For each of these sections, the IRI and the BBI were calculated. To compare the description of the pavement surface quality provided by IRI, that determine a single value characterizing the whole section length, in this study it was decided to calculate the BBI for all the points belonging to the profile section, then picking up the maximum value among them.

As can be seen in Figure 6, a very low correlation ($R^2$=0.11) between IRI and BBI values was found. Furthermore, considering the acceptance thresholds of both indices reported in Figure 6, it can be noted that, in general, different roughness evaluation is obtained, according to the used method. In fact, considering both acceptable and unacceptable zones, the percentage of evaluation agreement for IRI and BBI results is equal to 52.6% (43.3% of profiles evaluated by both methods as acceptable, 9.3% of profiles assessed by both methods as unacceptable) for IRI limit of 2 m/km and equal to 56.7% (51.5%+5.2%) for IRI threshold of 2.7 m/km. In particular, most of the profiles characterized by BBI>1 and IRI<2.7 belongs to a single runway, characterized by significant deformations due to deeper layers failure. From this first result, it seems that the agreement between these two roughness evaluation methods is not very high and the difference obtained considering the two above mentioned IRI acceptance thresholds is quite low. In addition, also when both indices (BBI and IRI) evaluate a profile section as unacceptable, they provide fairly different indication on the unacceptable severity level; in fact, a generic point representative of a profile section may be more or less far from the indices thresholds depicted in Figure 6.

The high percentage for dissimilar results provided by the two different approaches can be explained analyzing the spatial frequency content of the examined real profiles, and in particular, remembering that real profiles are non-stationary signals, thus, not all wavelengths are present along the whole profile length.

An example can be found analyzing in detail two profiles, marked as P1 and P2 (the third profile marked as P3 in Figure 6 was interested by further analyzes that are going to be described later), having similar IRI values but different BBI ones (Table 1). In order to highlight the difference in the spatial frequency content of the two profiles, the wavelet analysis (Daubechies 1990) is carried out (Figure 7a and Figure 7b). Wavelet analysis is becoming a common tool for analyzing localized variations of power within a time series. In this paper, this function was used to transform a profile from a one-dimensional spatial series to a diffuse two-dimensional spatial-frequency image. As can be noted comparing the Wavelet Transform (WT) results for P1 and P2 profiles with the correspondent BBI maximum values for each point along the whole profile (Figure 7c and Figure 7d), a good agreement between the long wavelengths content (low spatial frequency) and the location of the BBI highest peaks is found, with particular reference to profile P2. On the contrary, IRI evaluation is not able to describe the differences existing between these two profiles. Furthermore, the highest BBI value for P2 is located at around 50 m, where long wavelengths are present as shown in Figure 7b.

As can be seen in Figure 7b, in correspondence of the maximum BBI value found for profile P2 there are meaningful harmonic components having both short and long wavelengths. Because of the presence of low wavelengths, analyzing the IRI values calculated along the profile P2, depicted in Figure 8, it is found a significant increment of IRI value at the same position of the BBI peak along the path. Anyway, it should be remembered that the IRI value assigned to the examined section (in this case assigned to P2 profile) is the final one, calculated in correspondence of the segment length chosen for its calculation. In fact, IRI was not developed to evaluate punctual irregularities but distributed ones and, although IRI thresholds are often specified in road applications considering short segment of 7.6 m in order to detect areas of localized roughness in road profiles (Merritt et al. 2015), it cannot be used to assess the effect of punctual irregularities on aircrafts response. On the contrary, BBI method is designed to evaluate single bump event causing possible detrimental effect on aircrafts response.

However, also the BBI evaluation presents some limitations, in fact, it is unable to assess the effects on aircrafts of a series events present along airport pavements. For this reason, some authors recommend to use simulation models (Van Gelder and Stet 2009, Chen and Chou 2004) in order to correctly assess the effects on aircrafts due to airport pavements roughness condition. Therefore, the B727 simulation analysis with the ProFAA software (ProFAA Users's manual, 2004), considering a velocity of 100 knots, was performed for all the real runway profiles sample, comparing then the results with the ones obtained using BBI and IRI methods. In particular, due to the importance of pilots reports on runways roughness, as reported by the Transport Canada AC 302-023 ("*If pilot complaints of runway roughness are received and the RCI is at an acceptable level, then the runway profile should be evaluated for individual bumps of excessive magnitude*"), it was decided to assess the ability of IRI and BBI to predict cockpit vertical acceleration. Thus, the cockpit vertical acceleration maximum absolute value for each profile section was picked up and then compared with the correspondent BBI and IRI values. As acceptance threshold for the vertical acceleration, the ±0.4g criterion (CROW Report D07-03a) was used.

As can be seen in Figure 9, a moderate correlation ($R^2$=0.59) between BBI values and cockpit vertical accelerations was found. Furthermore, the simulation and the Boeing Bump approaches provide similar results for the 82.5% (54.6%+27.9%) of the examined cases, in terms of whether a runway section can be judged acceptable or not.

Thus, it can be said that a quite good matching between them was found. On the contrary, considering the comparison between IRI values and the calculated cockpit vertical accelerations (Figure 10), no correlation was found in agreement with a study carried out by Chen and Chou (2004) where the incapacity of the quarter-car used for IRI calculation to represent aircrafts response is described. In addition, a lower percentage of evaluation agreement both for IRI limit of 2 m/km (equal to 63.9%) and for the threshold of 2.7 m/km (equal to 70.1%) was found between IRI and simulation results. In any case, adopting both IRI acceptance thresholds, a quite large amount of runway sections was judged as acceptable using IRI method (21.6% for IRI limit of 2 m/km and 24.7% for IRI limit of 2.7 m/km), while they provide excessive vertical accelerations of cockpit. Using BBI method, instead, a low percentage (around 7%) of sections inducing excessive accelerations but assessed as acceptable by the Boeing approach was found. These results are a confirmation of the better capacity of the BBI method than IRI to predict cockpit vertical acceleration induced by airport pavements roughness.

Once more, it should be recalled that the BBI method is designed to assess single bump event along the airfield pavement profile, while simulation programs can also evaluate the effects on aircraft response due to the presence of series of bumps. For example, considering the P3 profile (Figure 11a) the correspondent BBI maximum value is lower than 1 (equal to 0.93), while estimating the cockpit vertical acceleration (Figure 11b) an unacceptable amount around 37 m is found. The different evaluation between the two methods can be explained due to the presence of a series of irregular events between 20 m and 40 m, which may affect aircrafts response.

Comparing BBI and aircrafts response simulation models, it is necessary to keep in mind that the first one has a general characterization of the runway roughness effects on different type of airplane, while the second one needs the development of a specific model for each kind of aircraft because of the different response to pavements roughness (Cardoso 2007a). Thus, to evaluate correctly airfield pavement roughness using simulation models, it would be needed to consider all the type of aircrafts traveling on the examined runway.

As seen in the preliminary study with regard to artificial sinusoidal profiles, one of the main causes of the differences obtained using BBI and IRI approaches can be found in their different sensitivity to long wavelengths. Neglecting the real runway profiles mainly characterized by long wavelengths roughness (> 40 m), a higher correlation between IRI and BBI was found ($R^2$=0.91) and reported in Figure 12.

In this case, IRI approach would seem to be a more restrictive criterion than BBI. In particular, the adoption of an IRI acceptance limit of 2 m/km would seem to be too conservative, corresponding to a BBI threshold equal to 0.45; while the use of the IRI limit of 2.7 m/km would enable the achievement of BBI values at least equal to 0.6.

These results show that also in case of runway roughness characterized by a predominance of low wavelengths, the BBI method remains more effective than IRI to represent the effects on aircraft response due the presence of irregularities along the runway profiles. Thus, the roughness evaluation of runways by the BBI method undoubtedly provides a more significant description of airfield pavements condition, to be used in a proper Airport Pavement Management System (APMS).

## Conclusions

In this paper, several real runway profiles were analyzed using different approaches to evaluate airfield pavement roughness. The comparison of the results obtained with them, has shown how using IRI approach could lead to wrong decision in pavement maintenance, mainly when irregularities characterized by long wavelengths are present along runway profiles; having several consequences like the underestimation of cockpit vertical accelerations. In particular, several limits in the use of IRI for the assessment of airfield pavement roughness were highlighted:

- IRI quarter car model is not fully representative of real aircraft response to rough runway;
- even if runway profiles are measured using Class I devices, the correct assessment of the effects on aircraft operations of long wavelengths is not possible;
- although the IRI method is able to locate roughness zones along runway profiles, it is not able to adequately assess the effects on aircrafts response. Thus, it cannot correctly say whether these localized roughness areas need maintenance actions or not, with regard to the transit of aircrafts..

On the contrary, the BBI method was found to be useful in the evaluation of airfield pavements quality, considering the quite good results agreement with other approaches like the ProFAA simulation analysis; although it is designed to assess single bump event.

Considering just runway profiles characterized by short wavelengths roughness, a very good correlation between IRI and BBI was found ($R^2$=0.91), although the correspondence between their acceptance thresholds was not so good. In fact, for the sample analyzed, it was found that in this case the IRI approach seemed to be more restrictive with regard to the BBI method. Thus, also when runway roughness is characterized by wavelengths within IRI operability range, the use of IRI method could lead to incorrect pavement roughness evaluation; overestimating, in this case, the effects on aircrafts response, if compared with the BBI approach.

Two different IRI acceptance limits were taken into account, the first one (equal to 2 m/km) is adopted in South Africa, while the second one is adopted in Canada (equal to 2.7 m/km) and it refers to a RCI value of 5. Considering the whole sample of runway profiles, it was found that little differences were obtained, in terms of percentage agreement with both BBI and cockpit vertical acceleration in the evaluation of the analyzed sections. In particular, it was found that both IRI thresholds provide a large amount (between 20-25%) of profiles judged as acceptable, while they induce excessive cockpit accelerations (>0.4g). On the contrary, using the BBI method, this percentage is reduced to a value of around 7%.

Analyzing just the profiles characterized by short wavelengths roughness (<40 m), it was found that the IRI acceptance threshold adopted in South Africa would seem to be too restrictive; thus, the adoption of the Canadian limit (equal to 2.7 m/km) would be preferable.

As confirmed by the analysis of profile P3, the BBI method is not able to evaluate the effects on aircrafts of a series of events present along runways profiles. For this reason, for a better management of airfield pavements, both evaluation criteria (BBI and simulations) should be used considering that in an airport pavement network many conditions of usage are present. On the contrary, IRI evaluation, even if very popular and easy to perform, may give results uncorrected that could alter the whole management process.

In order to adequately perform the Boeing method, which is capable of assessing the effects of the long wavelengths content in runway profiles on aircraft response, it is strongly recommended to utilize true profiles as input for BBI calculation; that means to measure airfield pavement profiles using Class I devices.

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Table 1. P1 and P2 profiles: IRI and BBI values.

| ***Profile id.*** | ***IRI (m/km)*** | ***BBI*** |
|---|---|---|
| *P1* | 3.81 | 0.81 |
| *P2* | 3.99 | 1.06 |

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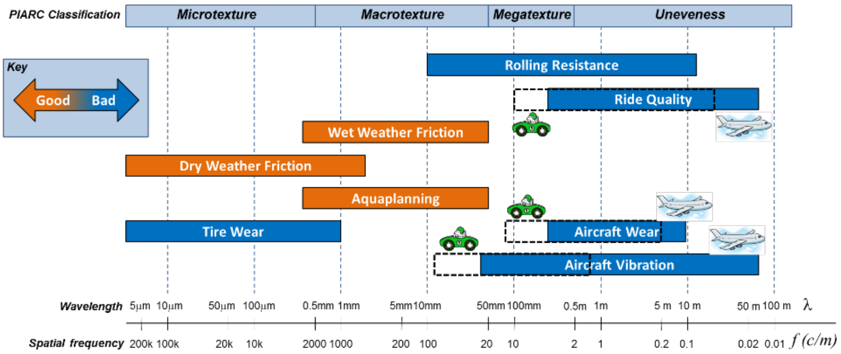

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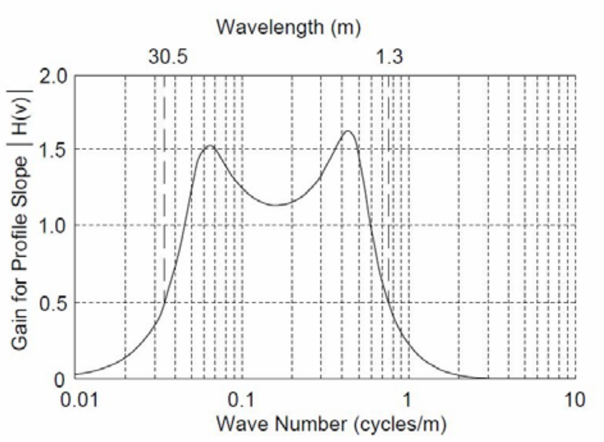

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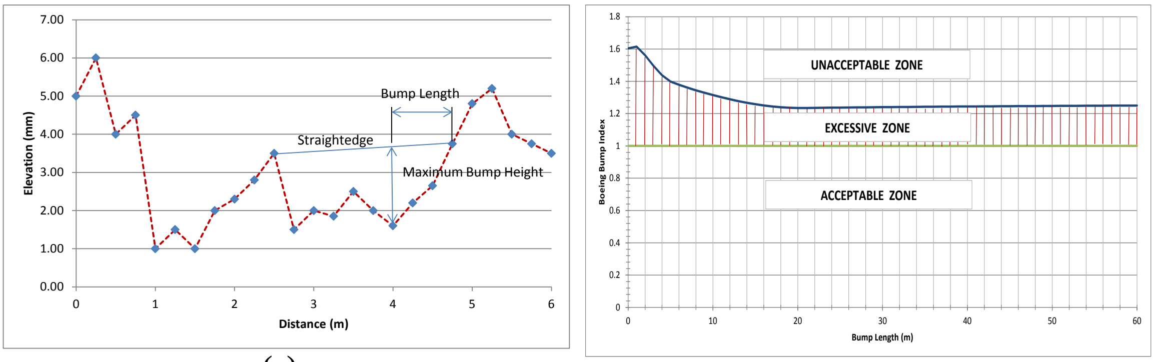
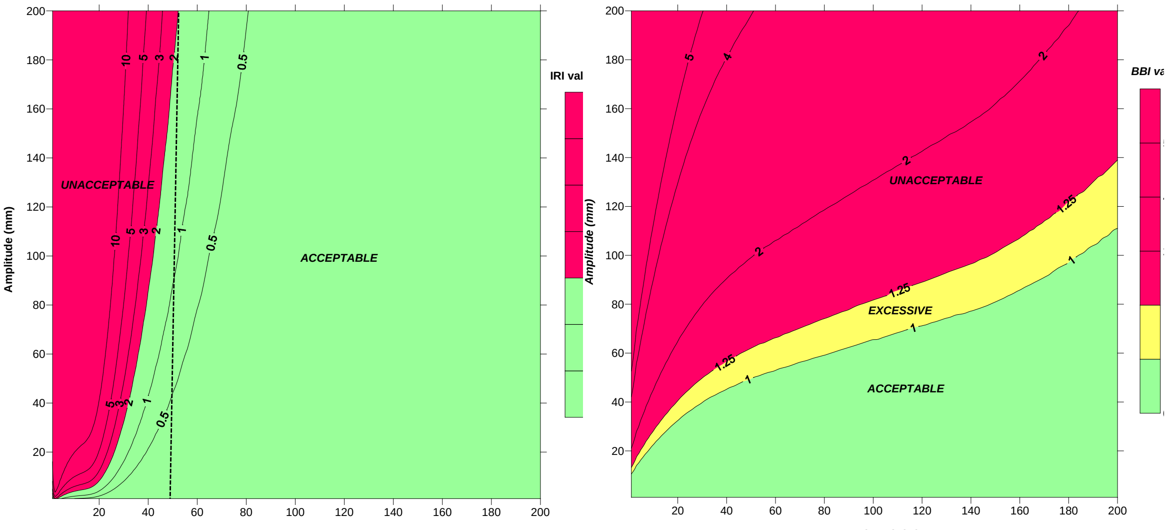


(a)

(b)

**Fig. 3. (a) Bump Height scheme and (b) BBI acceptance criteria.**



(a) (b)

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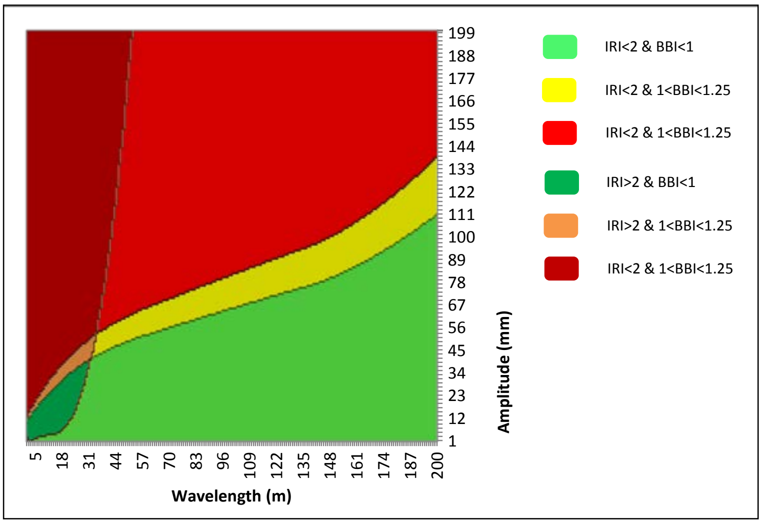


**Figure 5. Sinusoidal profiles influence on IRI and BBI overlapping plot.**

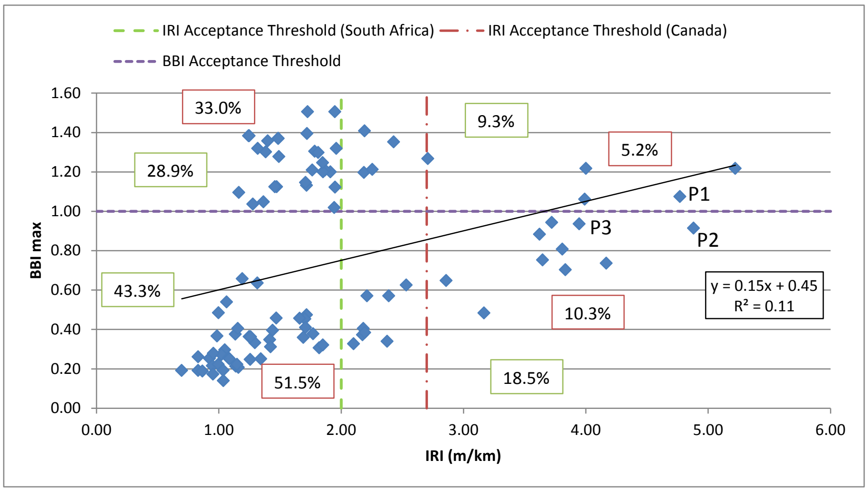
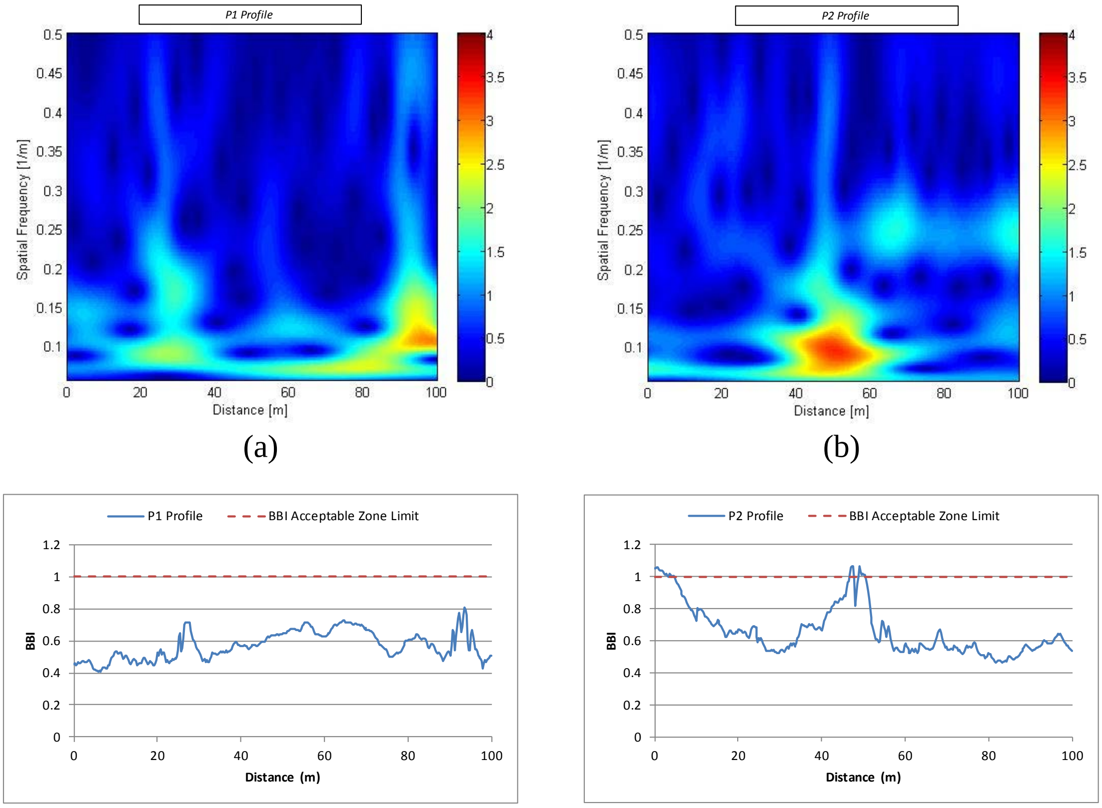


Figure 6. IRI and BBI values for the analyzed profiles.



(a) (b)

(c) (d)

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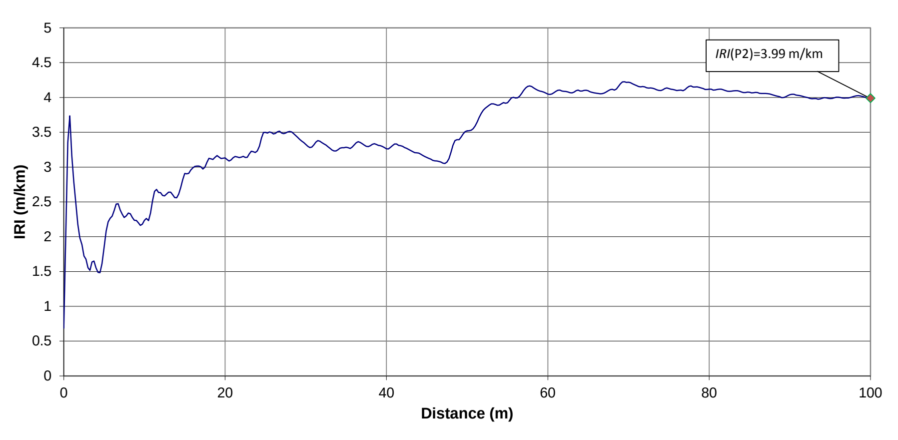

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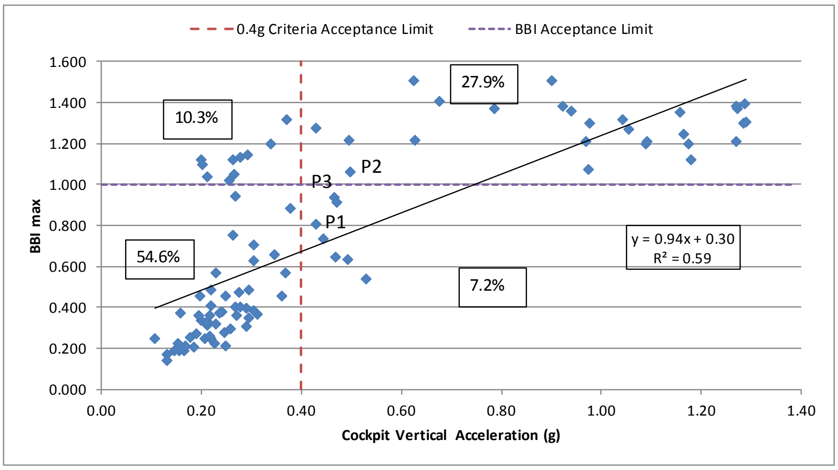

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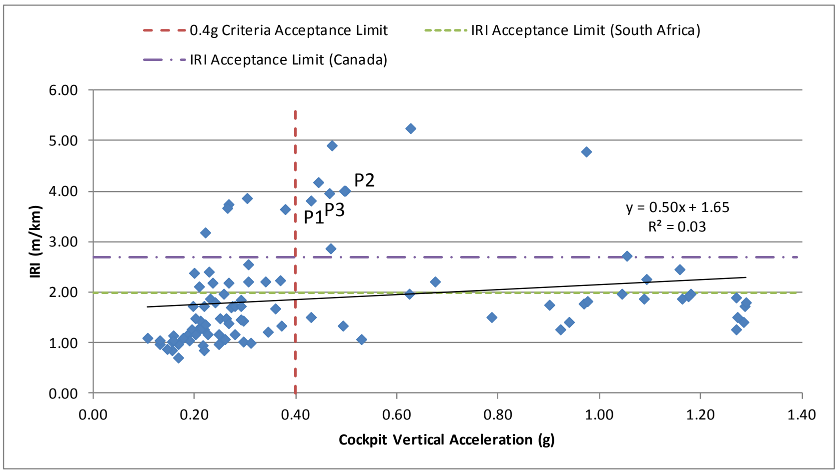

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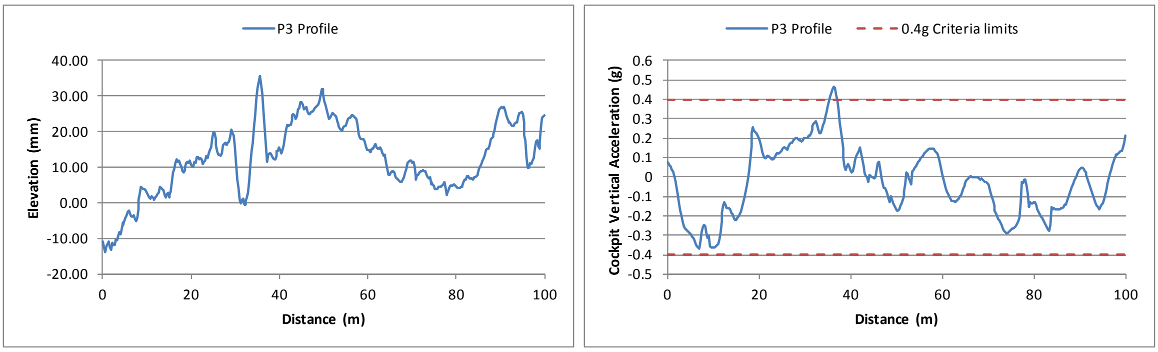

(a) (b)

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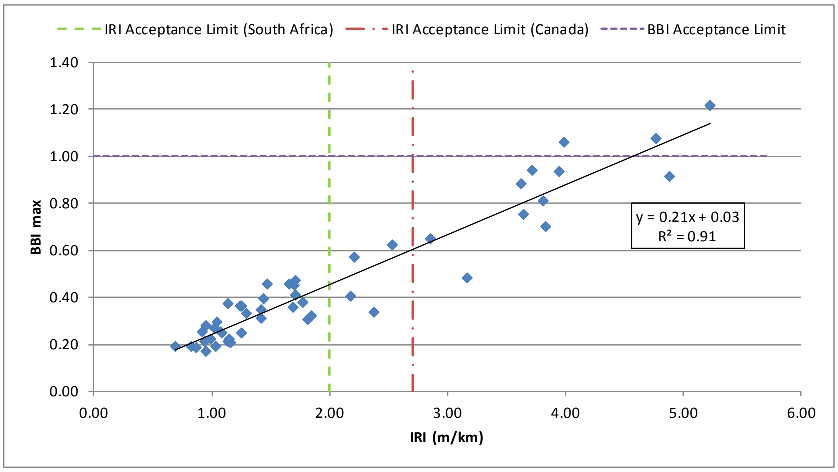

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